Soiling in CSP: modeling and forecasting from weather inputs

German Aerospace Center (DLR), Plataforma Solar de Almería, Spain

Fabian Wolfertstetter, Stefan Wilbert, Natalie Hanrieder, Lothar Keller, Sergio Gonzalez Rodriguez, Pascal Kuhn, Bijan Nouri

fabian.wolfertstetter@dlr.de

+34 950611877

Outline

- Intro and short recap of PV-CSP-soiling comparison
- Measurements and sites
- Soiling model architecture, training and validation
- Results and performance of soiling model
- Summary and outlook

DLR Energy meteorology group at CIEMAT's Plataforma Solar de Almería, the largest CSP research facility

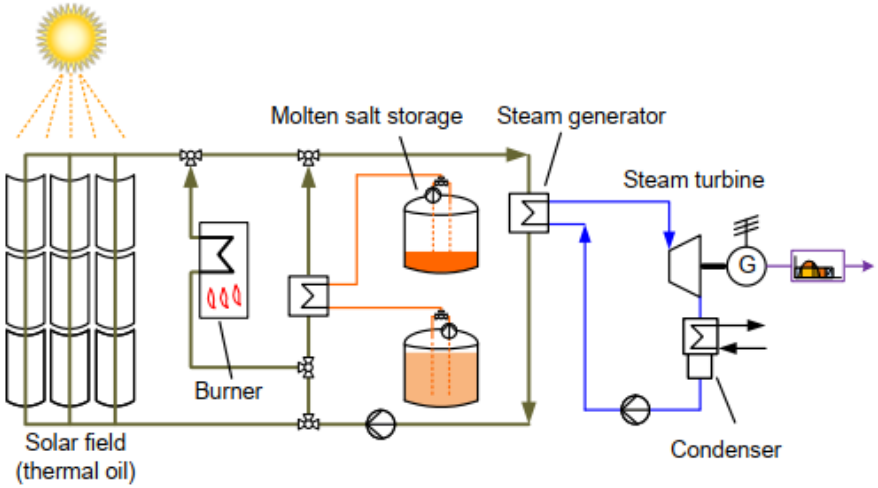
Research topics in CSP and PV:

- Soiling
- Degradation & abrasion of solar materials
- Attenuation of radiation
- Circumsolar radiation
- All-sky imager based nowcasting
- Shadow camera based measurements
- Atmospheric measurements

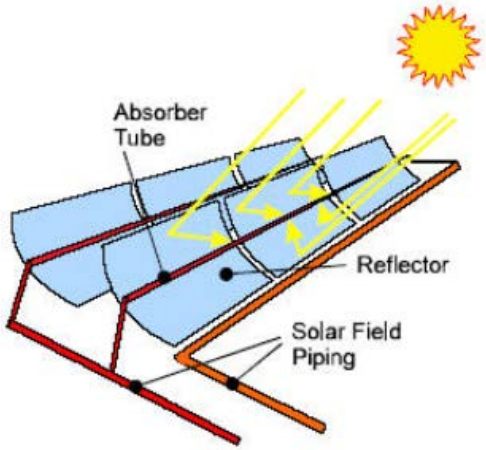
http://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10224/17488_read-44933/

DLR

Concentrating Solar Power

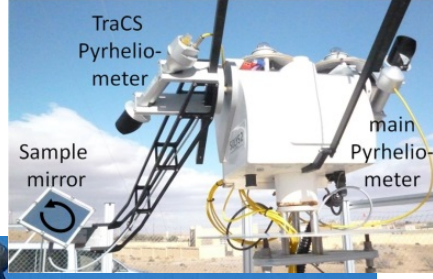


- Concentration of direct sunlight with mirrors to achieve high temperatures
- Provision of electricity (turbine cycle), process heat, desalination
- CSP uses only **direct component** of solar irradiation
- Cost effective **thermal storage** option
- **Grid stabilizing** effect thanks to turbine

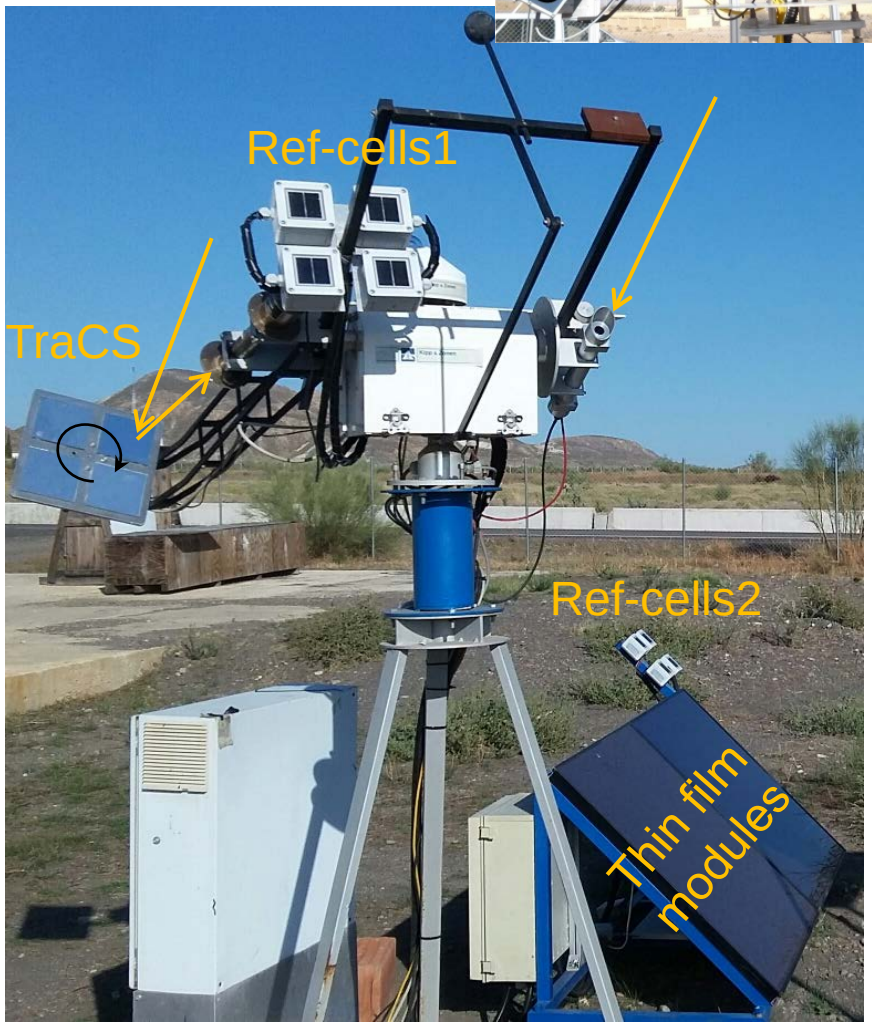


Images property of: Torresol energy, MASEN, SolarPACES, [T]

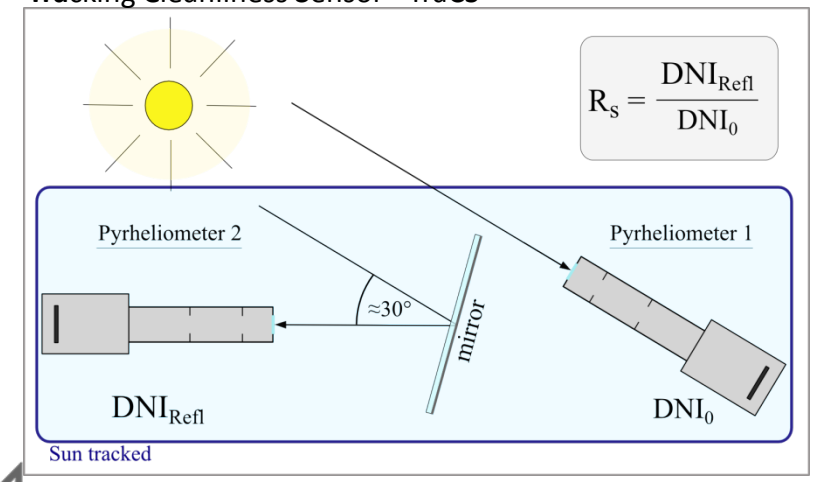
Measurement of Soiling of CSP mirrors



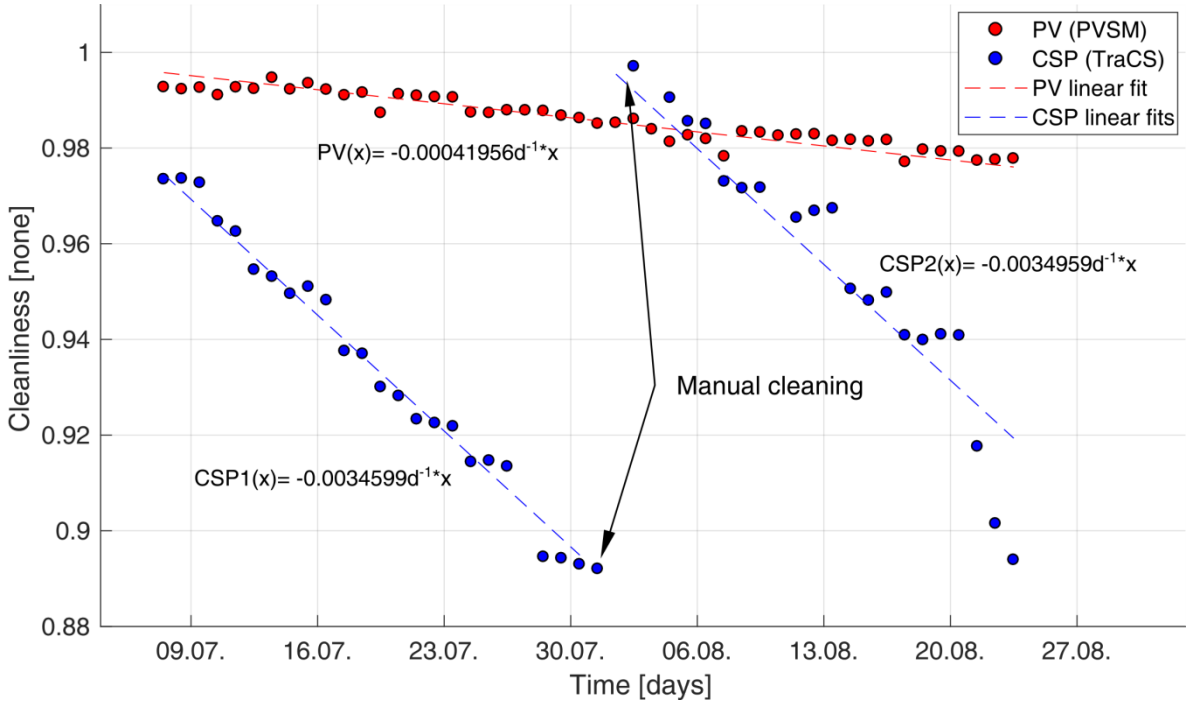
- Solar weighted specular reflectance ρ
- Cleanliness = ρ_{soiled} / ρ_{clean}
- TraCS: [W3]
  - Parallel real time measurement of 4 samples
  - Sun as light source
  - Rotation to increase measurement spot
- Handheld or lab devices [FG]
- 5 years of CSP soiling data at PSA



Tracking **C**leanliness **S**ensor - TraCS



Comparison of soiling



→ CSP soiling rate approx. **8-9 times higher** than PV (0.35%/d and 0.04%/d)

→ Assumption: same surface densities of dust and dirt

Soiling on a more global scale?

- Direct measurement of soiling is expensive and time consuming
- Project developers require more global data for site selection

Quest:

- Derive a soiling model and validate it locally
  - Model derives soiling rate from other weather parameters
- Possibly transfer model to a more global scale

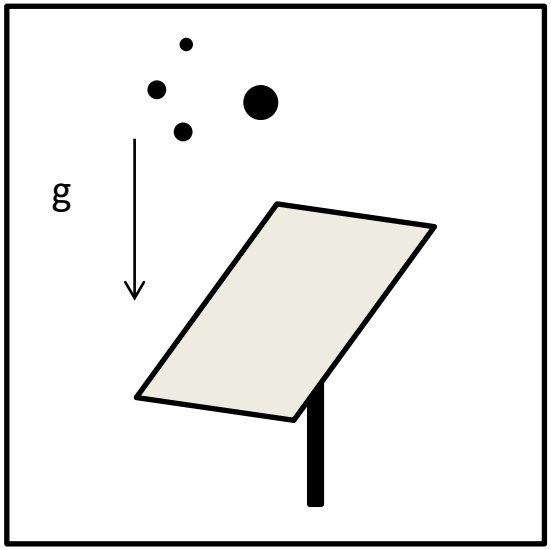
⇒make soiling estimation possible without direct measurements

⇒Integrate model into weather forecasting models

Soiling model: structure

In literature the deposition velocity characterizes particle deposition.
Deposition velocity: average velocity of a surrounding particle towards the mirror

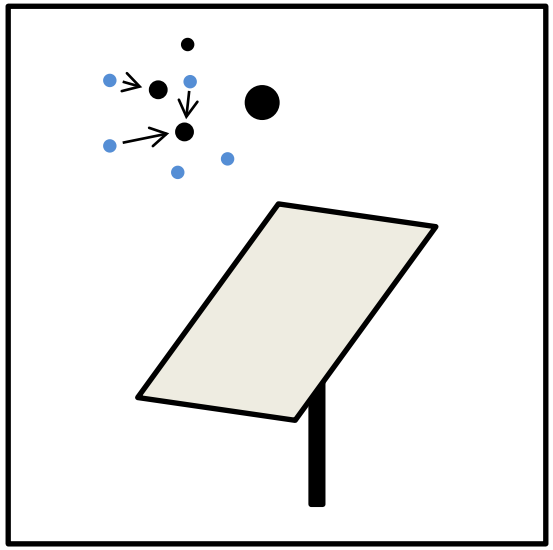
Sedimentation



- Gravitation

$$v_{S,p} = \frac{g\ {d_p}^2(\rho_{Aerosol} - \rho_{Luft})}{18\ \eta_{Luft}}$$

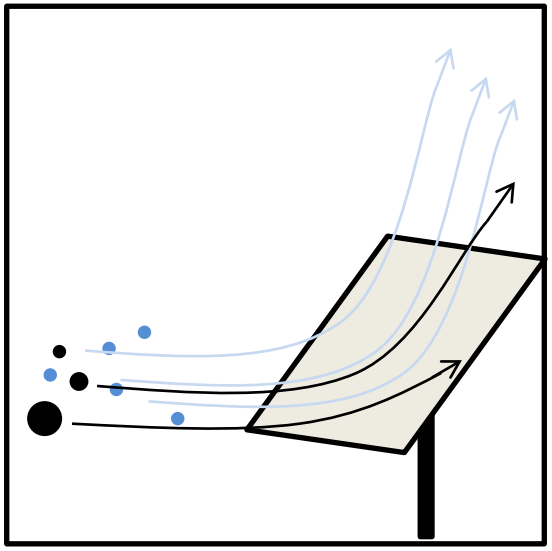
Brownian motion



- Thermal motion

$$v_B = a_{Brown}\ u_{Wind} \left(\frac{\nu_{Luft}}{D_B}\right)^{-\gamma}$$

Impaction



- Air stream/wind

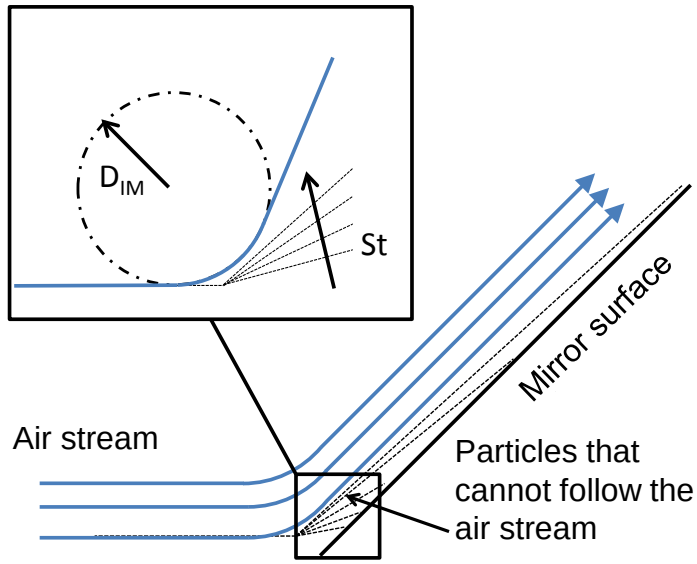
$$v_{Im} = a_{Im} \cdot \frac{\sigma_{Ausrichtung}\ u_{Wind}}{1 + \exp(-f_{Im} \cdot (St - 1))}$$

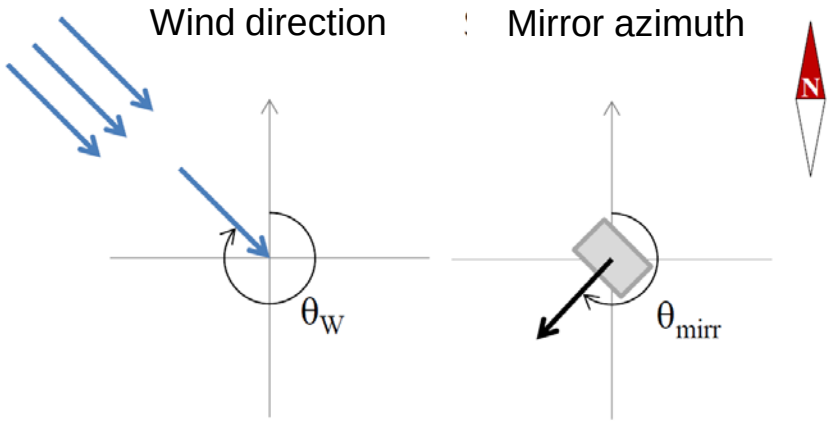
Also considered:
Rebound, resuspension, rain washing, cementation, mirror/panel orientation

Soiling model: impaction

$$St = \frac{\rho_{Aerosol}}{18\ \eta_{Luft}} \cdot {d_p}^2 \cdot \frac{u_{Wind}}{D_{Im}}$$

- Stokes number decides if particle follows the air flow (<1 = they follow)
  - Unknown in Stokes number is curvature of air flow D_{IM}
  - D_{IM} is dependent on impact angle of air flow
- CSP mirrors are tracked
- => Mirror orientation relative to wind speed for every time step is determined to calculate deposition velocity





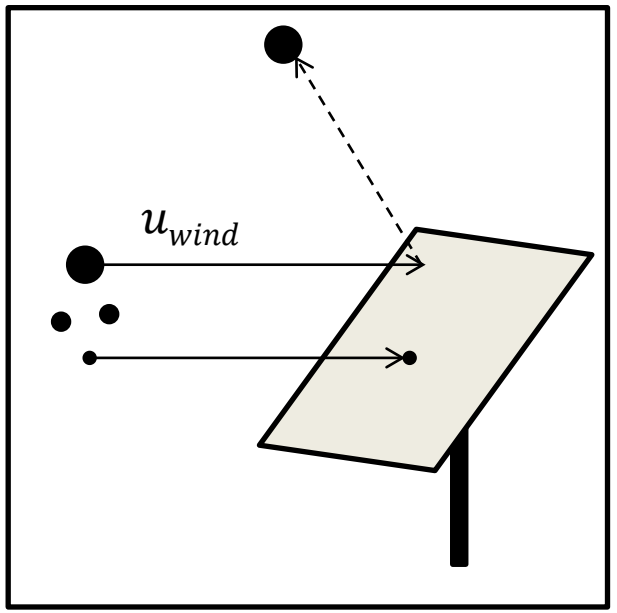
Soiling model: Particle rebound

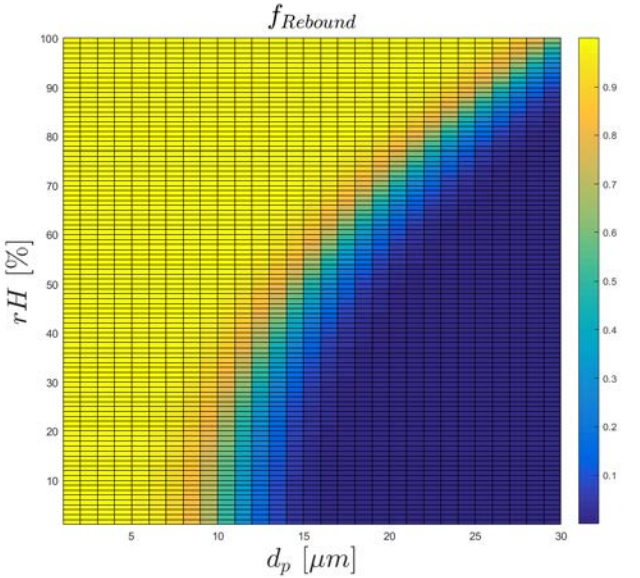
$$E_{kin} = \frac{1}{12}\ \rho_{Aerosol}\ {d_p}^3\ v_p^2$$ cles b urface $$E_a = \frac{A_{Hamaker}\ d_p}{12\ z_{Atom}}$$

- Described by sigmoidal:

$$f_{Rebound} = 1 - \frac{1}{1 + \exp(-f_{Reb}\ (d_p - d_{Rebound}))}$$

- Influence of relative humidity: high humidity makes rebound unlikely
- Relation from measurement

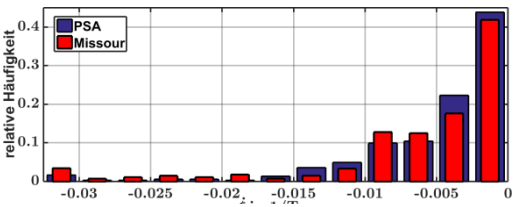




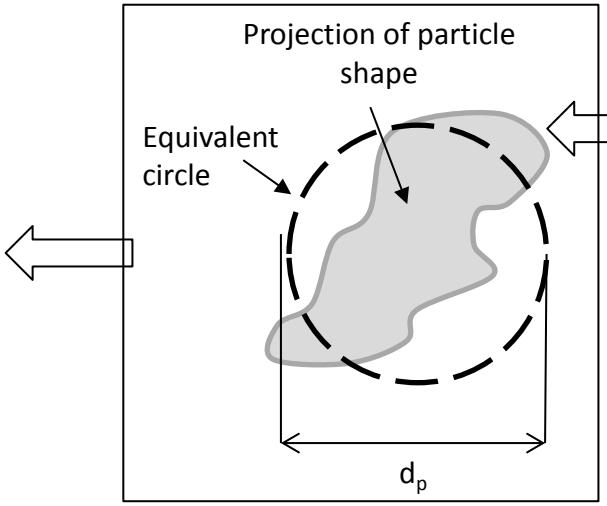
Soiling model: from depos. velocity to soiling rate

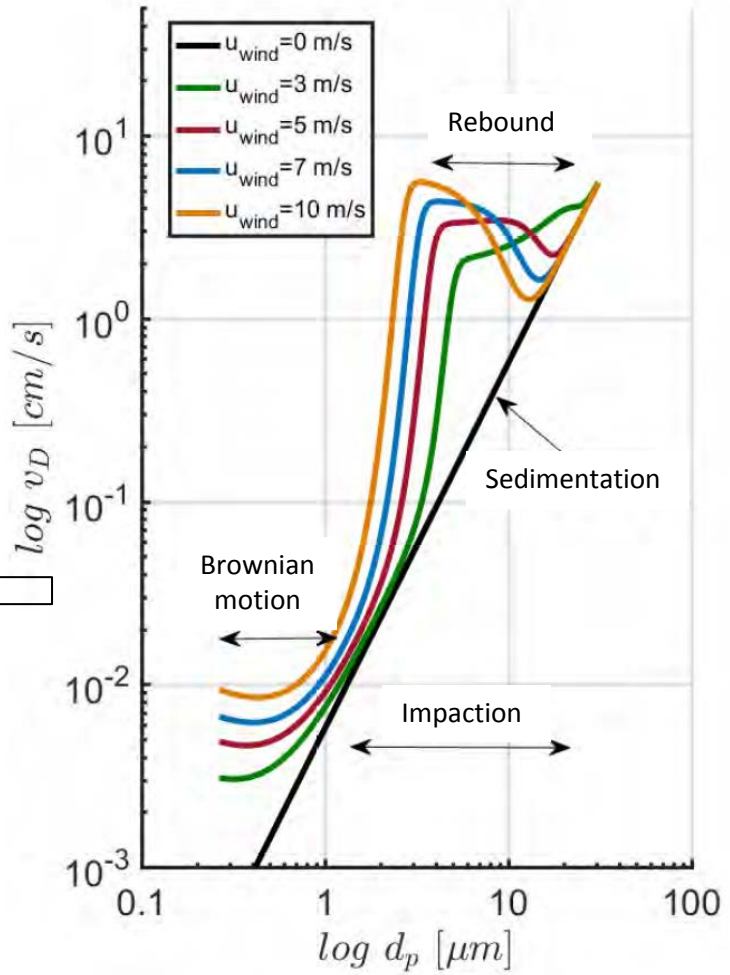
- Deposition velocity for various wind speeds agrees fairly well with literature

- Transfer to optical effect of soiling:
  - Determine covered surface
  - Linear correlation (from experiments) between soiling and covered surface to get soiling rate



Soiling rate in 1/d





Soiling model: from depos. velocity to soiling rate

Rate of surface coverage

Particle flux in [1/m²s]

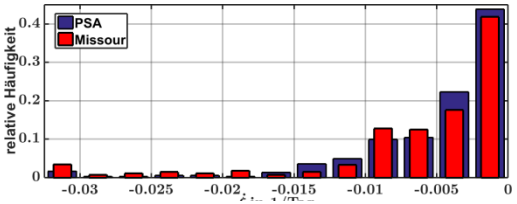
Projected surface in [m²]

$$AR(t_m) = \sum_{d_p=0{,}25\mu m}^{32\mu m} F(d_p, u_{Wind}, \alpha_{el}, ..., t_m) \cdot {d_p}^2 \cdot \frac{\pi}{4}$$

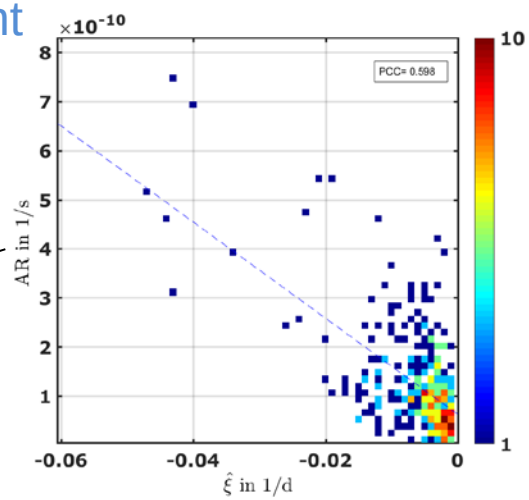
$$= \sum_{d_p=0{,}25\mu m}^{32\mu m} v_D(d_p, u_{Wind}, \alpha_{el}, ..., t_m) \cdot C(d_p, t_m) \cdot {d_p}^2 \cdot \frac{\pi}{4}$$

From main depos process modelling

From OPC measurement

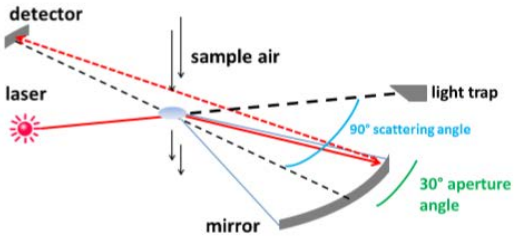


Soiling rate in 1/d

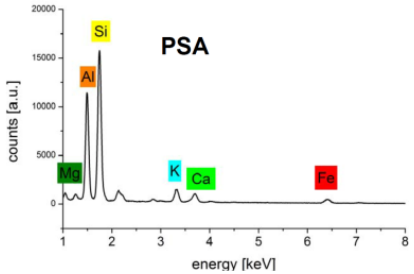


Soiling model: input data and parameterization

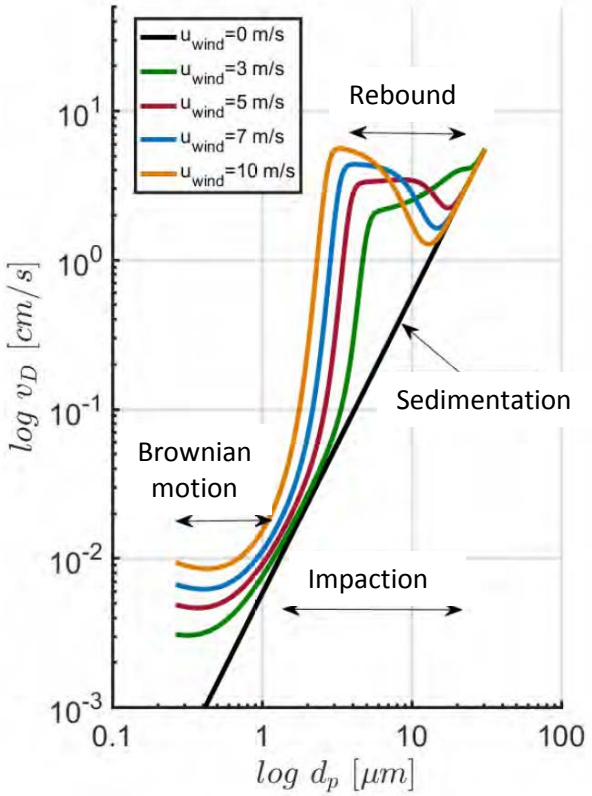
- **Model is trained** with a long term measurement dataset from PSA containing:
  - Aerosol particle number concentration from 0.25 µm - 30 µm
  - Wind, relative Humidity, rain, irradiance, dew, temperature, atmospheric pressure, etc.



Optical particle counter



Soil properties



Visibility

Flysand

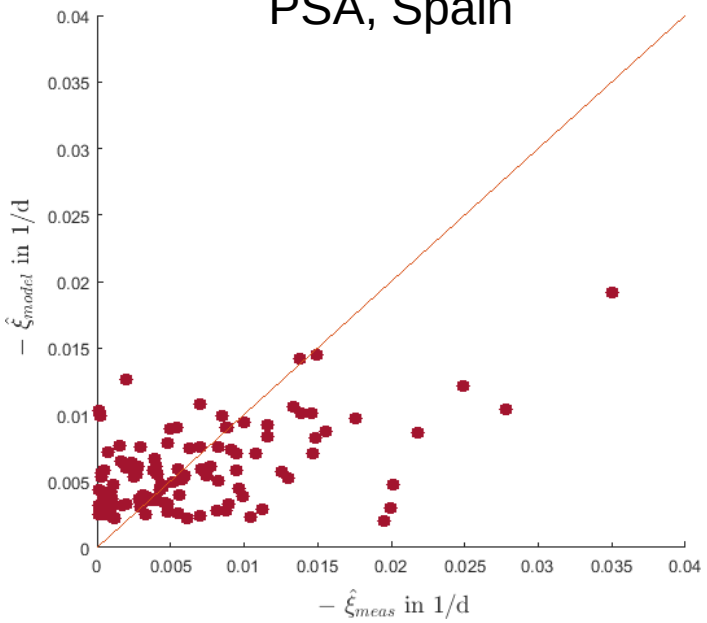
3D Wind, rain, temperature

Soiling model performance

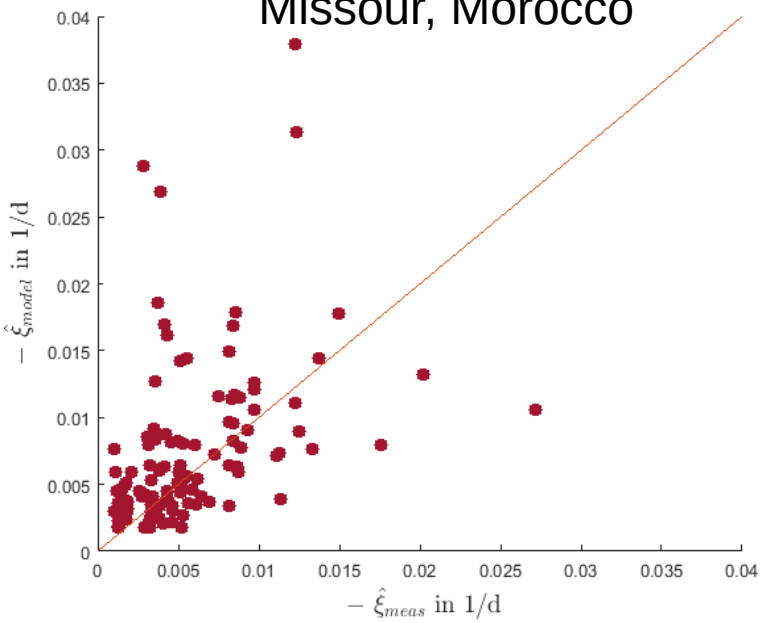
- Model validated for two sites
- RMSE = 2 x soiling rate measurement accuracy
- Bias = 0.5 x soiling rate meaurement accuracy

	Bias ($\cdot\ \%/d$)	RMSE ($\%/d$)
PSA Training Set	0.08	0.43
PSA Test Set	0.11	0.44
Missour	0.09	0.46

PSA, Spain



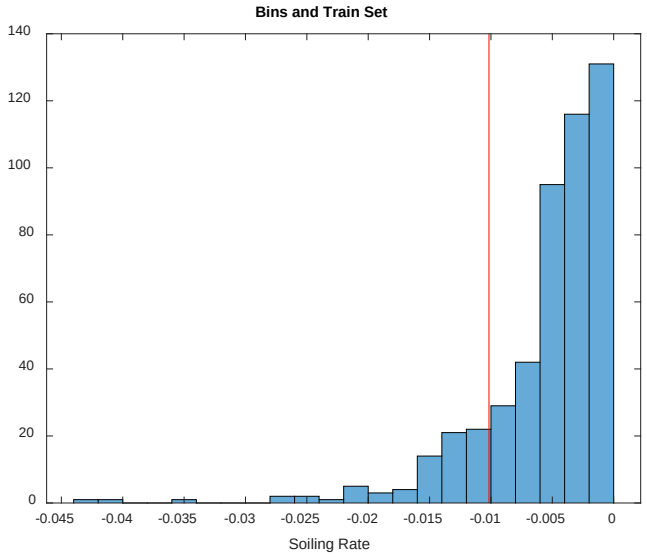
Missour, Morocco

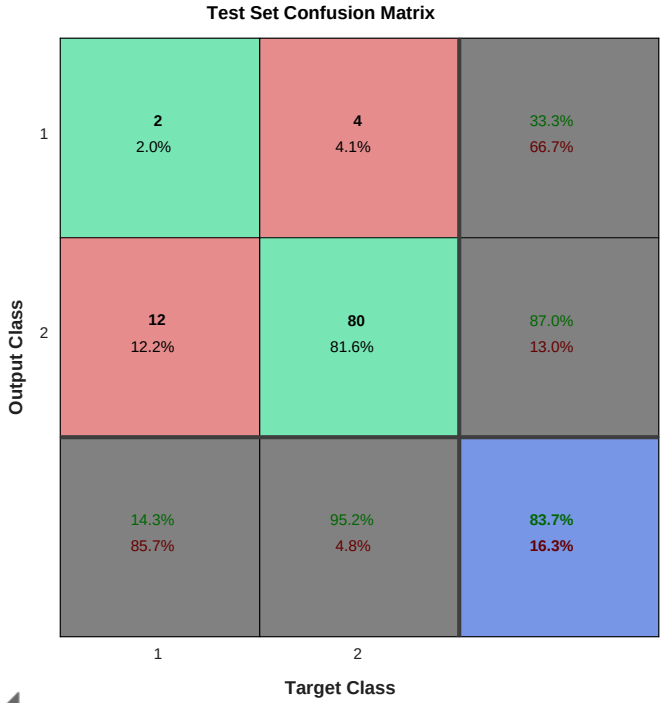


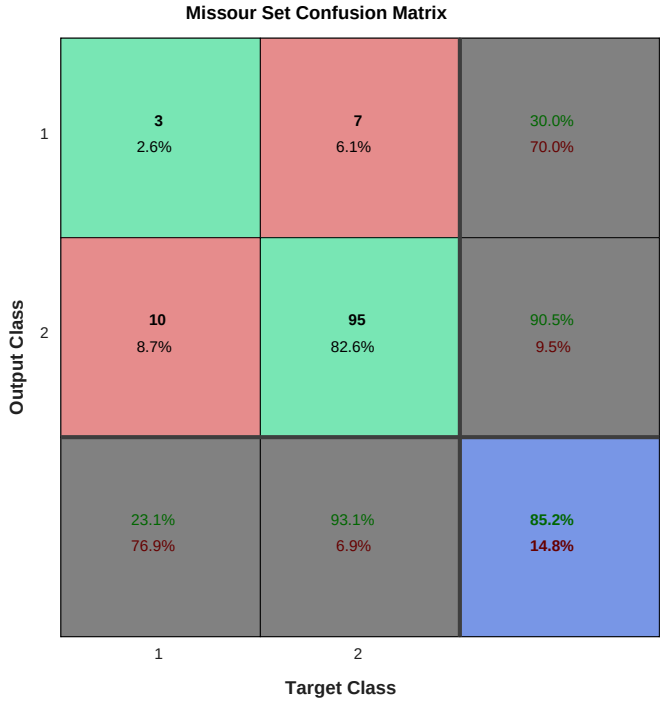
Soiling and condensation model applied to CSP solar field – DLR Report, WASCOP H2020 project D3.2, 2018, to be published online on www.wascop.eu,

Soiling model performance

- Approximate soiling information is often sufficient for cleaning scheduling
- Binning of soiling rate into low (<1 %/d) and high (>1 %/d) soiling rate
- result: low soiling days are predicted correctly with more than 90% probability



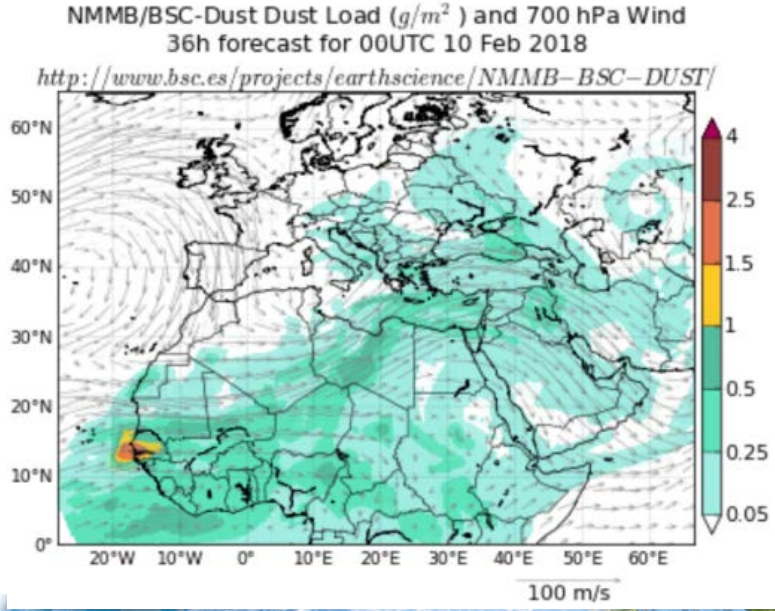




Outlook: Soiling rate map and forecast

- Atmospheric dust transport models :
  - Updated several times a day
  - Regional and global domains with 10 x 10 km^2 pixels
  - Forecast of atmospheric dust load and „deposition“
  - The model includes the weather parameters used in our soiling model

=> It is possible to integrate the CSP soiling model into dust transport models

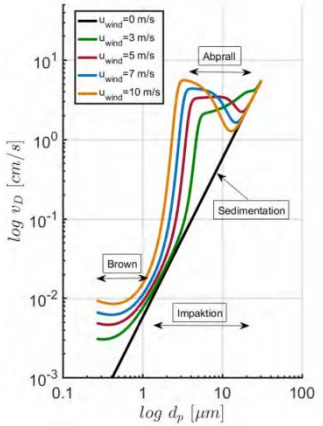


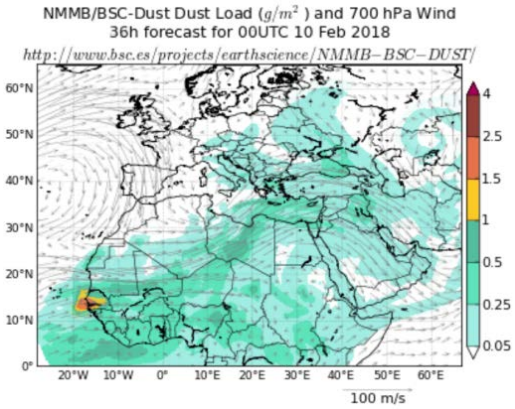
Outlook: Soiling rate map and forecast

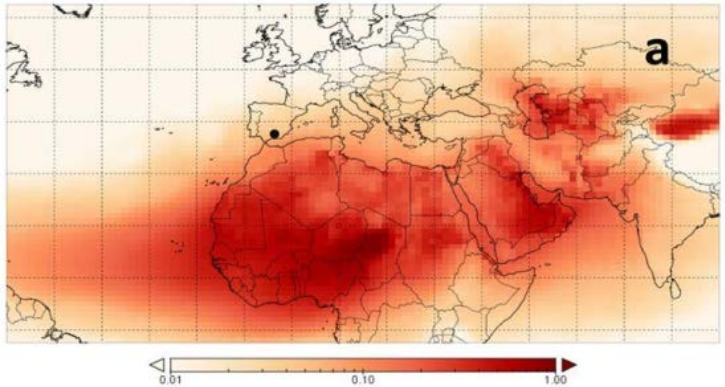
Activities within the solwatt project (https://solwatt.eu/) in collaboration with BSC:

- Couple the CSP soiling model with BSC atmospheric dust transport model
  - => soiling rate forecast of 72 hours
  - => soiling rate map from reanalysis of historical dust model data

- Covered last webinar: Transfer of CSP soiling to PV soiling is possible
  => PV soiling forecast and map are possible, not funded yet







Soiling measurement setup at PSA

PV reference cells

PV panels SCC comparison

TraCS for 4 mirrors

transmission measurement (tubes)

PV panels

TraCS for 4 mirrors

rain

Optical particle counter

visibility

wind

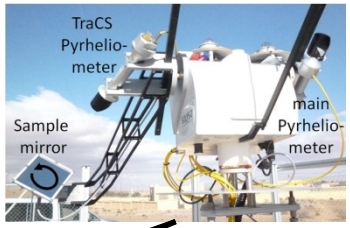
[S], https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-8680/12865_read-32404/

enerMENA network **Operational since 2010 -2013**

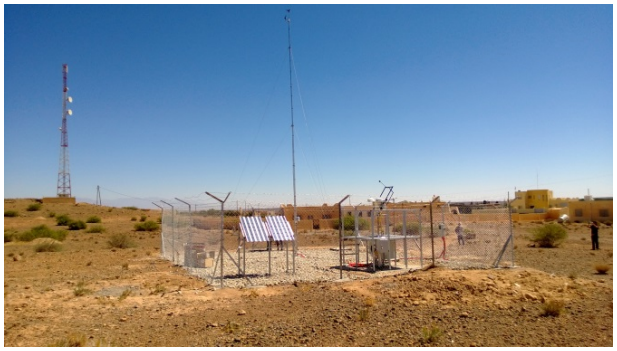
12 meteorological measurement stations (solar irradiance, temperature, pressure, relative humidity, wind, etc…)

Scatterometer FS11from Vaisala

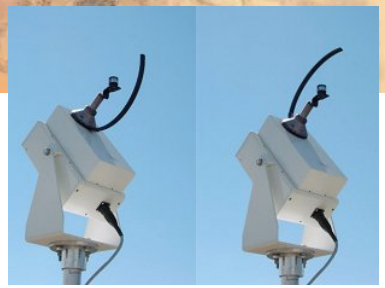
Grimm EDM164 Particle counter



TraCS for mirrror soiling



HVS-TSP16 from MCZ: gravimetric measurement principle



Thank you for your attention

fabian.wolfertstetter@dlr.de

References

[W4] **Wolfertstetter et al, „Soiling and Condensation model applied to CSP solar field“, WASCOP project report 3.2, 2018, http://wascop.eu/wp-content/uploads/2018/06/WASCOP_deliverable_3.2_final_plainText.pdf**

[Wi] **Wilbert**, S.: *Determination of Circumsolar Radiation and its Effect on Concentrating Solar Power.* PhD thesis, Technische Hochschule Aachen, 2014.

[W1] **Wolfertstetter**, F.*: Effects of soiling on concentrating solar power plants.* PhD thesis, Technische Hochschule (RWTH) Aachen, 2016

[K] **Knisely**, B., S. V. **Janakeeraman**, J. **Kuitche** . G. TamizhMani: *Validation of Draft International Electrotechnical Commission 61853-2 Standard: Angle of Incidence Effect on Photovoltaic Modules.* Arizona State University, Photovoltaic Reliability Laboratory, 2013.

[L] **Laven**, P.: *MiePlot - A computer program for scattering of light from a sphere using Mie theory & the Debye series.* Computer Program, 2017.

[Wa] **Wagner**, R., T. **Ajtai**, K. **Kandler**, K. Lieke, C. Linke, T. Müller, M. Schnaiter . M. Vragel: *Complex refractive indices of Saharan dust samples at visible and near UV wavelengths: a laboratory study. A*tmospheric Chemistry and Physics, 12(5):2491–2512, mar 2012.

[F] **Figgis**, B.: *PV Soiling: Qatar Perspective.* DEWA Soilingworkshop 2016*, 2016*

[T] THERMVOLT Systemvergleich von solarthermischen und photovoltaischen Kraftwerken für die Versorgungssicherheit Schlussbericht 01.11.2014 - 30.06.2016

[B] Bellmann, P., Oct. 2017, „**Investigation of soiling on mirror and glass samples with regard to power losses in CSP and PV technologies**“, Diploma thesis, University of Dresden

[Sc] Schüler, David, et al. "The enerMENA meteorological network–Solar radiation measurements in the MENA region." AIP Conference Proceedings. Vol. 1734. No. 1. AIP Publishing, 2016.

[W2] Wolfertstetter F, Wilbert S, Dersch J, Dieckmann S, Pitz-Paal R, Ghennioui A. Integration of Soiling-Rate Measurements and Cleaning Strategies in Yield Analysis of Parabolic Trough Plants. ASME. J. Sol. Energy Eng. 2018

[W3] Wolfertstetter, F., Pottler, K., Alami, A., Mezrhab, A., & Pitz-Paal, R. (2012). A novel method for automatic real-time monitoring of mirror soiling rates. SolarPACES 2012.

[FG] A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, C. Delord, Equipment and methods for measuring reflectance of concentrating solar reflector materials, Solar Energy Materials and Solar Cells, Volume 167, 2017

[S] Schüler, David, et al. "The enerMENA meteorological network–Solar radiation measurements in the MENA region." AIP Conference Proceedings. Vol. 1734. No. 1. AIP Publishing, 2016.

Soiling rate

- Soiling rate = reduction of cleanliness over time
- Soiling rate is dependent on time and location
- Not (yet) a standard measurement parameter
- Little information available in target regions for so